PB85-166155

Treatment of Drinking Water Containing Trichloroethylene and Related Industrial Solvents

(U.S.) Municipal Environmental Research Lab.
Cincinnati, OH

Aug 82

U.S. Department of Commerce
National Technical Information Service
NTIS

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. R
EPA/600/J-82/201		PB85-166155

4. TITLE AND SUBTITLE	5. REPORT DATE
TREATMENT OF DRINKING WATER CONTAINING TRICHLOROETHYLENE AND RELATED INDUSTRIAL SOLVENTS (Journal Version)	1982
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
O. Thomas Love, Jr., Richard G. Eilers	N/A
9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. PROGRAM ELEMENT NO.
USEPA/WERL/DWRD 26 West St. Clair Street Cincinnati, OH 45268	CNBC1A
	11. CONTRACT/GRANT NO.
	Inhouse
12. SPONSORING AGENCY NAME AND ADDRESS	13. TYPE OF REPORT AND PERIOD COVERED
Same	Final - 8/82
	14. SPONSORING AGENCY CODE
	EPA/600/14

15. SUPPLEMENTARY NOTES
Published in American Water Works Association Journal, 74(8):413-425, Aug. 1982

16. ABSTRACT

Volatile chlorinated and non-chlorinated compounds occur in both untreated and treated drinking water. Because volatilization is restricted, ground waters rather than surface waters are more likely to have high concentrations of these compounds. This document reviews properties, occurrence, and experiences, particularly laboratory and pilot scale, with the control of the following compounds:

tri- and tetrachloroethylene; cis- and trans-1,2-dichloroethylene; 1,1-dichloroethylene; vinyl and methylene chloride; 1,1,1-trichloroethane; 1,2-dichloroethane; carbon tetrachloride; benzene; chlorobenzene; 1,2-, 1,3-, and 1,4-dichlorobenzene; and 1,2,4-trichlorobenzene

Conventional water treatment will not generally reduce the concentrations of these compounds, but they can be reduced by aeration, adsorption on granular activated carbon or synthetic resins, or combinations of these processes. Boiling can also be effective for home treatment of these contaminants.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Water Treatment Cost Estimates Activated Carbon Treatment Aeration Industrial Wastes	Trichloroethylene Chlorination Volatile Compounds Ground Water Toxicity	13B

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES
RELEASE UNLIMITED	NONE	13
	20. SECURITY CLASS *(This page)*	22. PRICE
	NONE	

REPRODUCED BY
NATIONAL TECHNICAL INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

EPA/600/J-82/201
JOURNAL ARTICLE

Treatment of drinking water containing trichloroethylene and related industrial solvents

O. Thomas Love Jr. and Richard G. Eilers

Laboratory and pilot-scale studies have been carried out to ascertain the effects of aeration, adsorption, and boiling on water containing volatile organic solvents. These treatment methods are discussed, estimates of treatment costs are made, and data on the characteristics of the following compounds are given: trichloroethylene, tetrachloroethylene, 1,1,1-trichloroethane, cis-1,2-dichloroethylene, carbon tetrachloride, and 1,2-dichloroethane.

Several chlorinated hydrocarbon solvents—trichloroethylene, tetrachloroethylene, 1,1,1-trichloroethane, cis-1,2-dichloroethylene, carbon tetrachloride, and 1,2-dichloroethane—are undergoing review for possible inclusion in the National Revised Drinking Water Regulations.[1] Monitoring, assessing risk, and determining achievable target levels for chlorinated hydrocarbon solvents are ongoing. This paper reviews the existence of these solvents in water sources, compiles the general properties of these organic compounds, and summarizes some of the available treatment data.* Most of this treatment information was obtained through laboratory and pilot-scale studies that used aeration and adsorption. Cost estimates for these treatment processes were made by combining theoretical concepts with the available empirical data.

*This paper summarizes a portion of a more detailed document: Treatment for the Control of Selected Volatile Organic Compounds in Drinking Water. USEPA, Ofce. Res. Devel., Municipal Environ. Res. Lab., Drinking Water Res. Div., Cincinnati, Ohio (in press).

Occurrences in water sources

Trichloroethylene and related solvents do not occur naturally, and because of their volatility, they are seldom detected in concentrations greater than a few micrograms per litre in surface waters. One exception does occur, however. Bodies of fresh water receiving wastewater discharges may contain elevated concentrations of organic solvents during periods of ice cover when volatilization is restricted. Seeger et al[2] demonstrated that water sampled from the Ohio River at Cincinnati during the winter of 1977 (almost 1290 km [800 mi] of upstream ice cover) contained high concentrations of

0003-150X/82/080413-13

Vol. 74(8):413-425

TABLE 1
Comparative data for trichloroethylene and related solvents

Parameter	Trichloroethylene	Tetrachloroethylene	cis-1,2-Dichloroethylene	1,1,1-Trichloroethane	1,2-Dichloroethane	Carbon Tetrachloride
Molecular weight—*g/mol*	132	166	97	133	99	154
Density—*g/mL*	1.46	1.62	1.29	1.34	1.24	1.59
Boiling point—°C						
Atmospheric	87	121	60	74	84	77
Azeotropic (with water)[17]	73	88	NR*	65	72	67
Solubility—*mg/L*	1000[18] 1100[19,20]	150[18,19] 140[20]	3500[20]	4400[18] 5497[19]	8700[18,20]	800[18–20]
Vapor pressure—*mm Hg*[19,20]	74	19	206	100	82	91
Henry's law constant						
$\frac{\text{concentration in air}}{\text{concentration in water}}$	0.48[18]; 0.49[20]	1.1[18]; 1.2[20]	0.31[20]	0.17[18]; 1.2[20]	0.05[18,20]	1.2[18,20]
$\frac{\text{atm-m}^3}{\text{mol}}$[19]	$11.7 \cdot 10^{-3}$	$28.7 \cdot 10^{-3}$	NR	$4.92 \cdot 10^{-3}$	$1.10 \cdot 10^{-3}$	$30.2 \cdot 10^{-3}$
Threshold odor—*μg/L*	500[21,22]	300[21]	NR	NR	2000[21,22]	inconclusive†
Parachor[24]	212.8	250.0	175.6	223.9	186.6	220.0
Molar refraction[24]	30.42	35.21	20.71	24.95	21.18	26.30

*Not reported
†Test was inconclusive. Two of seven panel members reported detection at a concentration of 400*μg/L* (in unpublished study by USEPA-DWRD).[23]

TABLE 2
Removal of volatile organic compounds from drinking water by using diffused-air aeration (USEPA-DWRD pilot-scale studies)*

Location of Study	Compound	Average Influent Concentration *μg/L*	Average Effluent Concentration—*μg/L* at Various Air-to-Water Ratios†							Remarks
			1:1	2:1	3:1	4:1	8:1	16:1	20:1	
Cincinnati, Ohio	Tetrachloroethylene	1025	698	416	304	158	16			The tap water was spiked with these solvents.
		636	161	177	46	34	8	<1	<1	
		338	139	103	47	34	4	1	2	
		114	32	17	7	4	<1	<1	<1	
		107	32	17	7	4	<1	<1	<1	
		17	3	2	1	1	<1	<1	<1	
	Trichloroethylene	1064	796	614	508	319	53			
		397	223	273	102	82	22	<1	<1	
		241	136	110	61	53	8	2	3	
		110	40	28	18	9	3	<1	<1	
		73	22	14	8	6	1	<1	<1	
New Jersey	Tetrachloroethylene	94				9				The groundwater was contaminated by industrial discharge.
	Trichloroethylene	3				0.4				The pilot-scale column was run continuously for over one year.
	1,1,1-Trichloroethane	237				23				
	cis-1,2-Dichloroethylene	0.5				<0.1				
	1,2-Dichloroethane	1.4				0.8				

*All studies used a 4-cm (1.5-in.) diameter glass column, a 10-min contact time, and a water depth of 0.8 m.
†Blank spaces indicate no tests were conducted.

volatile compounds such as carbon tetrachloride and tetrachloroethylene, had high threshold odor numbers, and generated subsequent consumer complaints about taste and odor.

Organic contaminants can enter an aquifer and be transported great distances because they have little affinity for soils.[3-5] Recent sampling[6-9] has revealed solvent-contaminated groundwaters in Massachusetts, Connecticut, New Hampshire, New York, New Jersey, Delaware, Rhode Island, Pennsylvania, Florida, Michigan, and California. This list likely will grow when other states examine the organic quality of their groundwaters. Among the volatile organics found in groundwaters, 1,1,1-trichloroethane and trichloroethylene are found most frequently and in the highest concentrations.

The US Environmental Protection Agency's Drinking Water Research Division (USEPA-DWRD) has found that contaminated groundwater usually contains two or more predominant organic compounds and several other identifiable ones of lesser concentrations. One reason for the variety of compounds in one location might be related to solvent purity. Because the end product of the manufacturing process depends on the temperature, degree of acidification, and chlorination during the process, a commercial grade solvent might have varying amounts of several related compounds (Figure 1). Another reason for the presence of various solvents in one location might be biological degradation of a parent compound.[10]

Frequently, within a well field, one well may be uncontaminated, yet a nearby well may contain 1-2 mg trichloroethylene/L and several hundred micrograms of tetrachloroethylene and 1,1,1-trichloroethane per litre. However, another well within the same area, but perhaps drawing from a different aquifer, may contain a preponderance of 1,1,1-trichloroethane and cis-1,2-dichloroethylene and have merely detectable quantities of trichloroethylene. Finally, the concentrations of contaminants in a well can be variable. At a project in Connecticut (described later), 1,1,1-trichloroethane concentrations ranged from 12 to 214 *μg/L* over the year-long study.

Several possible sources for these contaminants have been suggested.[11] Included are industrial discharges (by means of spreading on the land or improper disposal at dumps), landfill leachates, septic tank degreasers and similar products from individual households, sewer leaks, accidental spills, cleaning and rinsing agents used on tanks and machinery, leaking storage tanks, and treated wastes used for groundwater recharge. Although organic solvents from improper pump lubricants or from well drilling aids are not likely to be major contaminants, they should be recognized as potential sources. Sometimes the source of contamination is not obvious. Crane and Freeman,[12] for example, reported that trichloroethylene and tetrachloroethylene were two of sev-

TABLE 3
Removal of tetrachloroethylene from drinking water by adsorption*

Time in Operation weeks	Bed Volumes m^3 water/m^3 adsorbent	Average Concentration—μg/L		
		Influent	Effluent	
			Activated Carbon†	Resin‡
4	4 700	1367	<0.1	<0.1
8	9400	1984	<0.1	0.1
12	14 100	1950	0.1	<0.1
16	18 800	906	0.2	0.2
20	23 500	825	2.8	0.4

*The source of contamination was a pipe liner in the distribution system.[15] In this study by USEPA in Rhode Island, the empty bed contact time was 8.5 min and the approach velocity was 1.3 mm/s (2 gpm/sq ft).
†Filtrasorb® 400
‡Ambersorb® XE-340

TABLE 4
*Removal of volatile organic compounds from drinking water by boiling—summary**

Compound	Percent Remaining at Various Times of Boiling—min					n†
	1	2	3	5	10	
Trichloroethylene	17	11	7	5	<0.1	10
Tetrachloroethylene	8	4	2	1	<0.1	4
cis-1,2-Dichloroethylene	24	10	7	4	<0.1	2
1,1,1-Trichloroethane	20	15	5	4	<0.1	3
Carbon tetrachloride				1		2

*A compilation of USEPA-DWRD results and data from Lataille[35] and Combs[36]
†Number of experiments from which results were averaged

TABLE 5
*Effects of aeration on a solvent-contaminated groundwater**

Contaminant	Average Concentration—μg/L		Percent Removal	Henry's Law Constant
	Before Aeration	After Aeration†		
1,1-Dichloroethylene	122	4	97	6.3[20]
1,1,1-Trichloroethane	237	23	90	1.2[20]
Tetrachloroethylene	94	9	90	1.1[18,20]
Trichloroethylene	3	0.4	87	0.5[18,20]
cis-1,2-Dichloroethylene	0.5	<0.1	>80	0.31[20]
1,1-Dichloroethane	6	1	83	0.24[20]
1,2-Dichloroethane	1.4	0.8	42	0.05[18,20]

*USEPA-DWRD study in New Jersey
†Diffused-air aeration with a 10-min contact time, an air-to-water ratio (vol:vol) of 4:1, and a water depth of 0.8 m

eral solvents detected in the effluent from the anion-cation exchange resin used in their laboratory. The source of this contamination was traced to the distribution plant where the resin was sent for regeneration. The groundwater used in the regenerative process was contaminated with organic solvents that then contaminated the resin.

Occasionally, one or more of the solvents are detected in treated water, yet are not present in the source water. These solvents are not produced as by-products of chlorination in the disinfection process, as in the reaction of chlorine with naturally occurring organics to produce chloroform and related trihalomethanes (THMs). Carbon tetrachloride, however, is a known contaminant of chlorine produced by the graphite-anode process.[13] Contaminated chlorine can be a significant source of carbon tetrachloride in treated drinking water.[14] Similarly, other products used in the production and distribution of water also can be sources of organic contaminants. For example, tetrachloroethylene can be leached from polyvinyl-toluene-lined asbestos cement pipe,[15] and trichloroethylene is present in certain joint compounds used in reservoir liners and covers.[16] Specifications on chlorine and other materials that come in contact with drinking water should help alleviate these sources of organic contaminants. An even more challenging situation exists when these organic compounds occur in what was previously thought to be a groundwater source free of organic contaminants.

Characteristics of industrial solvents

In general, trichloroethylene and related compounds are volatile, nonflammable in air, and have poor solubility in water. These characteristics make them useful solvents; they are widely used in industries and households, on military bases, and even within water treatment plants for cleaning and degreasing. Several physical and chemical properties for these compounds[17-24] are summarized in Table 1.

Trichloroethylene. Trichloroethylene is known by many other names*:[25-27] TCE, 1,1,2-trichloroethylene, 1,2,2-trichloroethylene, trichloroethene, acetylene trichloride, ethinyl trichloride, ethylene trichloride, Triclene, Trielene, Trilene, Trichloran, Trichloren, Algylen, Trimar, Triline, Tri, Trethylene, Westrosol, Chlorilen, Gemalgene, Germalgene, Benzinol, 1,1-dichloro-2-chloroethylene, Blacsolv, Blancosolv, Cecolene, 1-chloroethylene, Chlorylen, Circosolv, Crawhaspol, Dowtri, Dukeron, Fleck-flip, Floc-flip, Lanadin, Lethurin, Nalco 4546, Nialk, Perm-a-clor, Petzinol, Philex, Triad, Trial, Triasol, Anamenth, Chorylen, Densinfluat, Fluate, Narcogen, Narkosoid, Threthylen, Threthylene, and Trilen.

Trichloroethylene is produced commercially by chlorinating ethylene or acetylene. Stringent regulations have resulted in a declining use of trichloroethylene. However, it has been a common ingredient in many household products (spot removers, rug cleaners, air fresheners), dry cleaning fluids, industrial metal cleaners and polishers, refrigerants, and even anesthetics.[28,29] The ubiquitous use of trichloroethylene probably explains why it is often the predominant synthetic organic contaminant in groundwater.

Tetrachloroethylene. The other names[25-27] by which tetrachloroethylene is known include: PCE, perchloroethylene, 1,1,2,2-tetrachloroethylene, tetrachloroethene, Ankilostin, carbon bichloride, carbon dichloride, Didakene, ENT-1860, ethylene tetrachloride, NCl-C04580, Nema, Perawin, Perc, Perclene, PerSec, Tetralex, Tetracap, Tetropil, Antisal, Fedal-Un, Tetlen, Tetraguer, and Tetraleno.

Tetrachloroethylene is produced commercially by chlorinating acetylene or ethylene dichloride. This solvent is used widely in dry cleaning, textile dyeing, metal degreasing, and synthesizing fluorocarbons.[28,29]

1,1,1-Trichloroethane. 1,1,1-Trichloroethane also is known by other names:[25-27] Methylchloroform, Chloroethene, Aerothene TT, Chlorten, NCl-C04626, alpha-trichloroethane, α-T, Chlorothane, Chlorothene NU, Chlorothene VG, Inhibisol, Methyltrichloromethane, and Trichloroethane.

1,1,1-Trichloroethane is produced commercially by reacting chlorine with vinyl chloride or by acidifying vinylidene chloride with hydrochloric acid. 1,1,1-Trichloroethane has replaced trichloroethylene in many industrial and household products. It is the principal solvent in septic tank degreasers, cutting oils, inks, shoe polishes, and many other products.[28,29,30]

Carbon tetrachloride. The other names by

*Mention of commercial products does not constitute approval or endorsement by USEPA.

TABLE 6

Adsorption of volatile organic compounds by granular activated carbon—summary

Compound	Average Concentration μg/L	Bed Depth m	Bed Depth ft	EBCT* min	Loading—m^3/m^3 Breakthrough of 0.1 μg/L (except as noted)	Loading—m^3/m^3 Exhaustion (influent = effluent)	Exhaustion Capacity† m^3/m^3	Reference
Trichloroethylene	177	0.8	2.5	9	>20 160	>20 160	21 500	USEPA-DWRD
	4	0.8	2.5	8.5	>60 900 but <123 340	>123 340	99 900	USEPA-DWRD
	3‡	0.8	2.5	18	>32 500	>32 500	106 560	USEPA-DWRD
	0.4§	0.8	2.5	18	>32 500	>32 500	199 800	USEPA-DWRD
Tetrachloroethylene	1400	0.8	2.5	9	12 300	33 100	17 500	USEPA-DWRD
	94‡	0.8	2.5	18	>32 500	>32 500	57 400	USEPA-DWRD
	9§	0.8	2.5	18	>32 500	>32 500	162 800	USEPA-DWRD
	4	0.8	2.5	8.5	>60 900 but <123 340	>123 340	237 600	USEPA-DWRD
	1	0.8	2.5	9	>20 160	>20 160	475 200	USEPA-DWRD
1,1,1-Trichloroethane	100	0.6	2	7.5	1 300**		3 800	40
		1.2	4	15	2 700**		3 800	40
		1.8	6	22.5	3 900**		3 800	40
	237‡	0.8	2.5	18	15 700	30 800	2 600	USEPA-DWRD
	23§	0.8	2.5	18	>32 500	>32 500	12 000	USEPA-DWRD
	38	0.8	2.5	8.5	11 800	26 000	9 400	USEPA-DWRD
	1	0.8	2.5	9	16 400	22 500	94 400	USEPA-DWRD
Carbon tetrachloride	12	0.8	2.5	10	14 000	25 000	9 400	46
		0.8	2.5	5	6 050		9 400	46
cis-1,2-Dichloroethylene††	18	0.8	2.5	6	4 100	15 800	9 400	36
		1.5	5	12	7 100	14 300	9 400	36
		2.3	7.5	18	8 100	13 700	9 400	36
	6	0.8	2.5	9	14 200	19 000	15 300	USEPA-DWRD
	2	0.8	2.5	8.5	29 600	48 600	26 000	USEPA-DWRD
1,2-Dichloroethane	8	0.8	2.5	20	1 700	8 640	3 500	47
	1.4‡	0.8	2.5	18	17 400	45 900	5 700	USEPA-DWRD
	0.8§	0.8	2.5	18	>32 500	>32 500	5 000	USEPA-DWRD
	2	0.9	3	11	3 300	9 160	4 000	47
		1.8	6	22	3 400	7 850	4 000	47
		2.7	9	33	4 150	>7 000	4 000	47
		3.6	12	44	>7 000	>7 000	4 000	47
		0.8	2.5	17.5	2 500	7 450	4 000	47
		0.7	2.4	17	2 500	7 450	4 000	47

*Empty bed contact time
†Estimated by Freundlich isotherms[47]
‡Adsorption of nonaerated water
§Adsorption after 10-min aeration; air-to-water ratio 4:1 (vol:vol)
**5 μg/L in effluent
††Isotherm capacities based on trans-1,2-dichloroethylene

which carbon tetrachloride is known include: Tetrachloromethane, perchloromethane, Necatorina, Benzinoform, methane tetrachloride, methane, tetrachloro-, Necatorine, ENT 4705, Halon 104, Carbon chloride, Carbona, Flukoids, R10, Tetrafinol, Tetraform, Tetrasol, Univerm, and Vermoestricid.

Carbon tetrachloride was once a popular household solvent, a dry cleaning agent, and a charging agent for fire extinguishers. Since 1970, however, carbon tetrachloride has been banned from all use in consumer goods in the United States, and in 1978 it was banned as an aerosol propellant. Currently, carbon tetrachloride is used principally in the manufacture of fluorocarbons that are used as refrigerants and, to a lesser degree, in grain fumigants.

cis-1,2-Dichloroethylene. cis-Acetylene dichloride, cis-1,2-dichloroethene, and NCl-C51581 are other names for cis-1,2-dichloroethylene.

This isomer of dichloroethylene is used both as a solvent and a fermentation retardant.[25]

1,2-Dichloroethane. 1,2-Dichloroethane has many other names:[25-27] 1,2-dichloroethane, Borer Sol, Brocide, Destraxol Borer-Sol, Dichloremulsion, Di-Chloro-Mulsion, dichloroethane, Alpha,beta-Dichloroethane, Dichloroethylene, Dutch liquid, EDC, ENT 1656, ethane dichloride, ethylene chloride, ethylene dichloride, glycol dichloride, NCl-C00511, Acetylene dichloride, and Dioform.

1,2-Dichloroethane is used as a solvent for fats, oils, waxes, gums, and resins.[25]

Laboratory and pilot-plant studies

Other than some incidental evaporative losses, conventional water treatment consisting of coagulation, settling, precipitative softening, filtration, and chlorination has been shown to be ineffective for reducing concentrations of trichloroethylene and related volatile organics.[2,31] Figure 2 illustrates two points: the ineffectiveness of conventional treatment to remove carbon tetrachloride, and the accentuated contaminant concentrations during the period of ice cover.

Aeration. USEPA-DWRD conducted several pilot-scale diffused-air aeration studies by using a 4-cm (1.5-in.) diameter glass column, 1.2 m (4 ft) long with a fritted glass diffuser in the bottom. The air and water flows were countercurrent and controlled with rotameters. A 380-L (100-gal) stainless steel tank was fitted with a floating lid to provide almost headspace-free storage of water that was either Cincinnati tap water spiked with one or more compounds or actual water at the site of a contaminated groundwater source in New Jersey. Water samples before and after aeration were collected, stored, and analyzed.[32] The results of these studies are given in Table 2.

Adsorption. From the published and unpublished reports that the authors reviewed,[2,33,34] powdered activated carbon (as it is used in taste and odor control) seems to have little effect on removing the volatile organics from drinking water. More promising adsorption performance, however, has been developed on granular adsorbents, and some of these projects and results are discussed in this paper.

In the summer and fall of 1977, the USEPA-DWRD installed pilot-scale adsorption columns at three sites in New England. Two different adsorbents were examined in 4-cm (1.5-in.) diameter glass columns. One test column contained 75 cm (30 in.) of granular activated carbon (GAC)* and a parallel column, 75 cm of synthetic resin.† Influent and effluent samples were collected weekly and shipped to USEPA laboratories in Cincinnati for analysis. At one of the three test sites (Rhode Island), the distribution system was contaminated by tetrachloroethylene.[15] The GAC maintained a con-

*Filtrasorb® 400, Calgon Corp., Pittsburgh, Pa.
†Ambersorb® XE-340, Rohm and Haas, Philadelphia, Pa.

TABLE 7
Adsorption of trichloroethylene and related solvents by the synthetic resin—summary*

Compound	Average Concentration μg/L	Bed Depth m	Bed Depth ft	Empty Bed Contact Time min	Loading to 0.1 μg/L in Effluent (except as noted) m^3/m^3	Reference
Trichloroethylene	215	0.3	1	2	83 700†	39
	210	0.6	2	4	78 600†	39
	210	1.2	4	7.5	>53 300†	39
	177	0.8	2.5	9	>20 160	11
	4	0.8	2.5	8.5	>123 340	USEPA-DWRD
	3	0.2	0.8	5	>117 000	USEPA-DWRD
Tetrachloroethylene	41	0.3	1	2	>99 900‡	39
	51	0.6	2	4	78 600‡	39
	65	1.2	4	7.5	>53 300‡	39
	70	0.3	1	2	106 000‡	39
	94	0.8	2.5	5	112 900	USEPA-DWRD
	1400	0.8	2.5	9	17 920	USEPA-DWRD
	3	0.8	2.5	8.5	>123 340	USEPA-DWRD
	2	0.8	2.5	9	>20 160	11
1,1,1-Trichloroethane	5	1.2	4	7.5	39 300‡	39
	33	0.8	2.5	9	56 000	11
	237	0.2	0.8	5	82 600	USEPA-DWRD
	23	0.2	0.8	5	>100 800	USEPA-DWRD
	1	0.8	2.5	9	>20 160	11
Carbon tetrachloride	19	0.8	2.5	5	7 560	11
	19	0.8	2.5	10	15 120	11
cis-1,2-Dichloroethylene	40	0.3	1	2	37 200‡	39
	38	0.6	2	4	39 500‡	39
	40	1.2	4	7.5	19 700‡	39
	40	0.3	1	2	36 400‡	39
	25	0.8	2.5	6	14 400	36
	22	0.8	2.5	6	7 200	36
	16	0.8	2.5	6	11 500	36
	6	0.8	2.5	9	>20 160	11
	2	0.8	2.5	8.5	>59 000 but <123 340	USEPA-DWRD
1,2-Dichloroethane	1	0.2	0.8	5	108 860	USEPA-DWRD

*Ambersorb® XE-340
†20 μg/L in effluent
‡5 μg/L in effluent

centration of tetrachloroethylene below 0.1 μg/L in the effluent for 11 weeks (Table 3). Because of inclement weather, the study was stopped after 20 weeks. At that time the resin was passing an average of 0.4 μg tetrachloroethylene/L. Although the resin is similar to the GAC in loading to breakthrough,* it exhibited a relatively flat breakthrough curve, showing a slow rate of contaminant movement through this resin relative to the wavefront movement through GAC.

The Rhode Island project was unique because the water applied to the adsorbents contained not only tetrachloroethylene but also residual chlorine, THMs (average of 140 μg/L), and a total organic carbon (TOC) concentration of 4 mg/L. The data in Table 3 indicate the performance of the adsorbents under conditions in which competition probably exists for adsorption sites.

The other pilot-scale adsorption projects started in 1977 by USEPA-DWRD were in New Hampshire and Connecticut at water utilities having contaminated wells. The groundwaters were not chlorinated, and the TOC concentrations ranged from 0.3 to 0.7 mg/L. Although the following adsorption results are presented for individual organic compounds, each groundwater contained a blend of solvents. In the New Hampshire study, trichloroethylene was the predominant contaminant and concentrations ranged from 120 to 276 μg/L. Unfortunately, after 18 weeks, the test column became clogged with what appeared to be precipitated iron. The contaminant wavefront was disrupted when the adsorbent was removed to clean the column, and the study was ended after 23 weeks (Figure 3). In the Connecticut study, trichloroethylene was one of the lesser contaminants, and concentrations ranged from <1 to 10 μg/L. The test columns were sampled weekly for one year, then allowed to run continuously, and resampled one year later. Trichloroethylene was removed to levels below detection (0.1 μg/L) for the first year, but the GAC was exhausted after two years, whereas the resin was still removing trichloroethylene at the time (Figure 3). Figures 4 and 5 show column performance for 1,1,1-trichloroethane and cis-1,2-dichloroethylene. Because both compounds broke through the GAC during the study, adsorption capacities could be determined. For the resin, breakthrough of 1,1,1-trichloroethane was evident at the end of the first year, but the adsorbent was not exhausted even at the end of the second year (Figure 4).

In 1978 a study began in New Jersey to examine the effectiveness of aeration and adsorption alone as well as combined. Water from a contaminated well was pumped intermittently into a stainless steel tank with a floating lid. Then the water was pumped to adsorption columns and an aerator (Figure 6). Water utility personnel maintained the equipment and collected and forwarded water samples weekly to USEPA-DWRD in Cincinnati.

The New Jersey study ran for 58 weeks. In the nonaerated water, tetrachloroethylene concentrations ranging from 60 to 206 μg/L (average 94 μg/L) were reduced to less than 0.1 μg/L by both adsorbents. The aerated water (average tetrachloroethylene concentration of 9 μg/L) behaved similarly. Figure 7 illustrates the adsorption of 1,1,1-trichloroethane before and after aeration. An interesting feature of these results is that resin performance is perhaps less improved than that of GAC when aerated water is applied. Perhaps aeration lessens the competition for adsorption sites on the nonspecific adsorbent—GAC.

Boiling. Boiling is sometimes suggested as a means for individuals to rid drinking water of volatile organics. Because boiling is not a standardized procedure, conditions are likely to vary between households. A summary of USEPA-DWRD results and other data[35,36] is presented in Table 4 to show that long boiling times can be effective because most of these organic compounds have an azeotropic boiling point (Table 1) below 100°C.

Discussion of water treatment processes

In full-scale water treatment plants, tetrachloroethylene,[2,31] cis-1,2-dichloroethylene,[31] 1,2-dichloroethane,[31,37] and carbon tetrachloride were not removed by coagulation, sedimentation, and filtration. Therefore, the effective control of other volatile organic compounds by conventional treatment is unlikely.

Aeration. Air stripping can successfully lower the concentration of volatile organics in drinking water. Because mixtures of solvents exist in contaminated water and even though the effectiveness of the process varies for each solvent, aerating to remove one specific contaminant will also reduce concentrations of the others. A typical example of this is given in Table 5. When aeration is used to remove tetrachloroethylene, the principal target and other solvents are removed. In this illustration, if the concentrations are simply added, the concentration of volatile organics in the water is approximately 460 μg/L before aeration and 40 μg/L afterward, for about 92 percent overall removal efficiency. As shown by

*For this discussion, breakthrough is the length of service when at least 0.1 μg/L of the contaminant is detected consistently in the effluent from the adsorbent. Length of service is expressed both in time and bed volumes (m^3water/m^3 adsorbent).

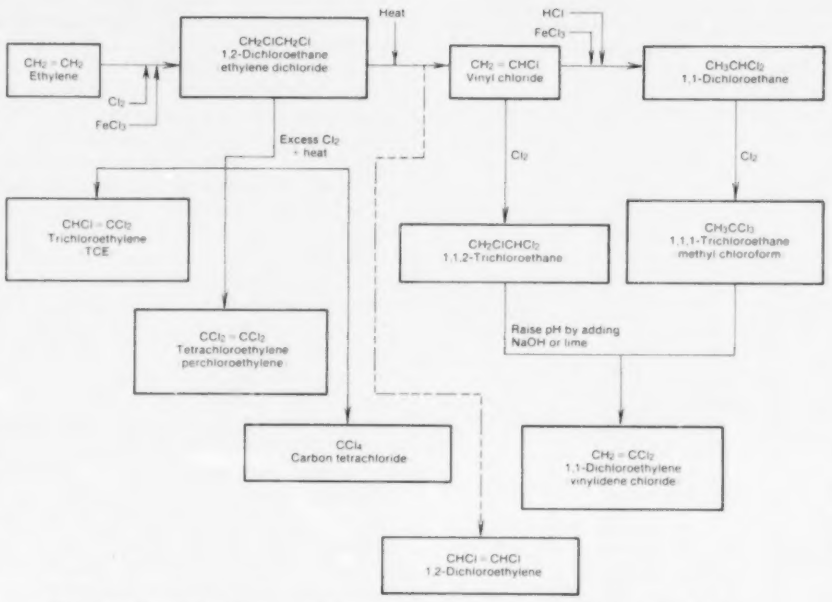


Figure 1. Simplified diagram of the manufacturing process for industrial solvents

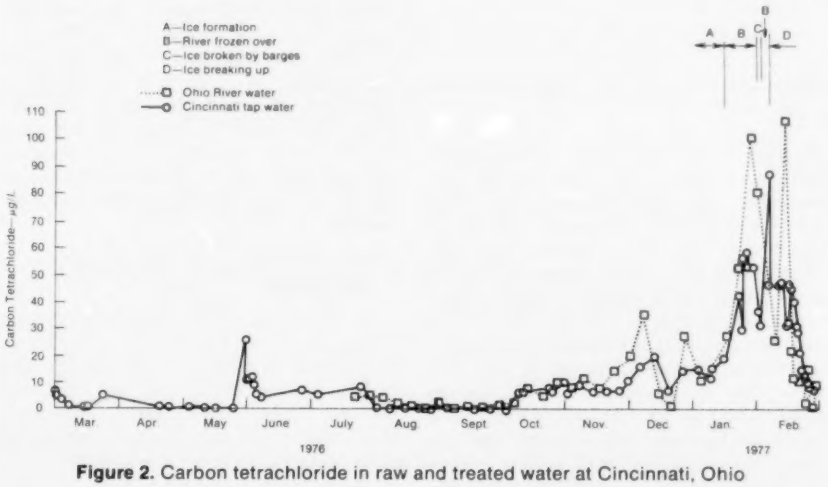


Figure 2. Carbon tetrachloride in raw and treated water at Cincinnati, Ohio

Water treatment consisted of powdered activated carbon, coagulation, settling, filtration, and chlorination.

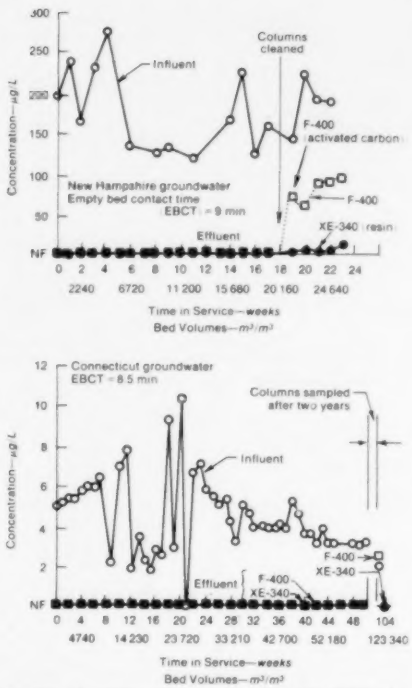


Figure 3. Removal of trichloroethylene by adsorption on granular activated carbon and polymeric resin

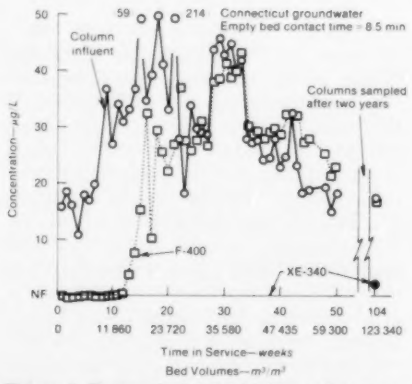


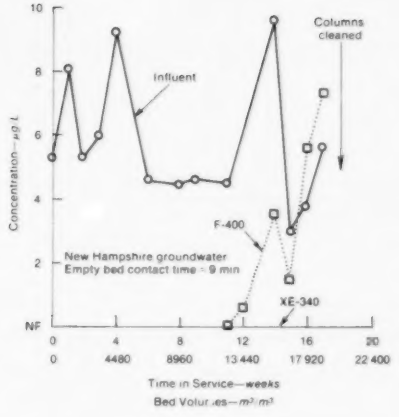
Figure 4. Removal of 1,1,1-trichloroethane on granular activated carbon and polymeric resin

McCarty et al[38] (and seen from the data in Table 5), the ease of removing a contaminant by aeration generally increases with increasing Henry's law constant.

Figures 8, 9, and 10 compare empirical data collected by USEPA-DWRD and other investigators[39,40] with the theoretical optimum removal by aeration. The optimum removal curve was developed by using the reciprocal of the Henry's law constants presented by Dilling.[20] A detailed explanation on developing the optimum removal curve was given by Symons et al.[41]

All of the data shown in Figures 8 through 10 were collected on pilot-scale devices that used either diffused-air or packed-tower aerators. Although data are limited for some of the organics, the trend suggests a deviation between the theoretical and actual air-to-water ratios necessary to achieve a high percentage of contaminant removal. The deviation between ratios is one order of magnitude or more. Whether these differences are the results of water quality influencing the volatility of certain compounds or simply problems in aerator design is not known and is the subject of ongoing research by USEPA-DWRD.

Questions have been raised concerning potential air quality problems created by exhaust gases from the aeration process.



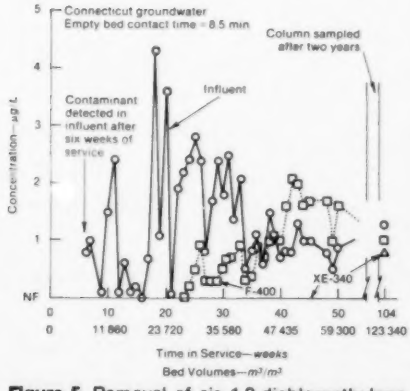
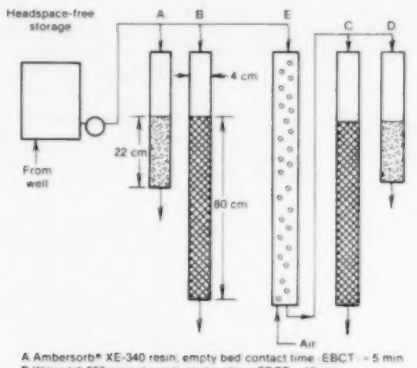
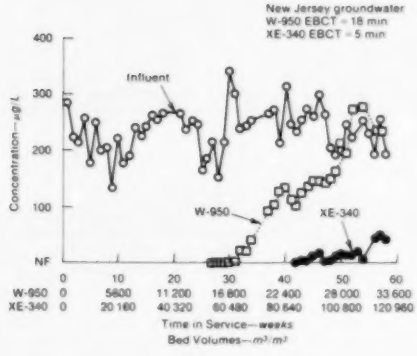


Figure 5. Removal of cis-1,2-dichloroethylene by adsorption on granular activated carbon and polymeric resin



A Ambersorb® XE-340 resin; empty bed contact time (EBCT) = 5 min
B Witcarb® 950 granular activated carbon; EBCT = 18 min
C Witcarb® 950 granular activated carbon; EBCT = 18 min
D Ambersorb® XE-340 resin; EBCT = 5 min
E Diffused-air aerator; 10-min contact time; 4:1 air:water

Figure 6. Illustration of USEPA–DWRD pilot-scale treatment used at contaminated well site in New Jersey



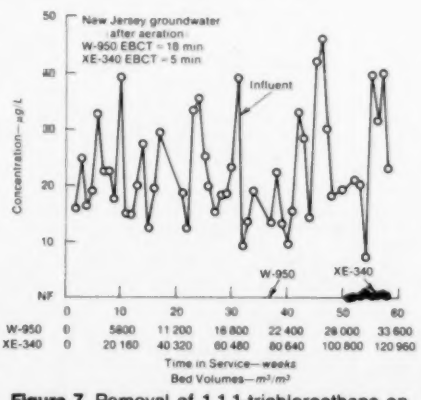


Figure 7. Removal of 1,1,1-trichloroethane on granular activated carbon and polymeric resin

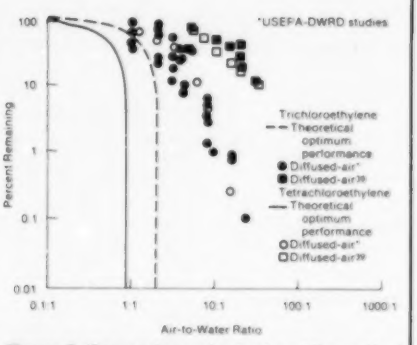


Figure 8. Comparison of actual and theoretical removal of trichloroethylene and tetrachloroethylene from drinking water by aeration

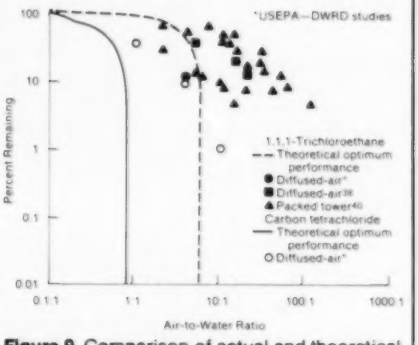


Figure 9. Comparison of actual and theoretical removal of 1,1,1-trichloroethane and carbon tetrachloride from drinking water by aeration

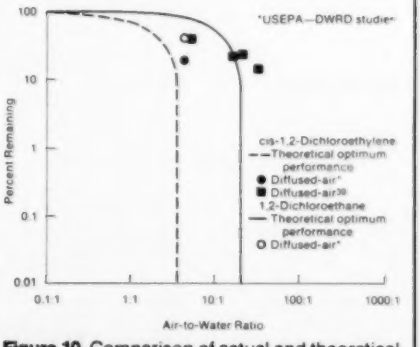


Figure 10. Comparison of actual and theoretical removal of cis-1,2-dichloroethylene and 1,2-dichloroethane from drinking water by aeration

In one USEPA-DWRD-sponsored aeration project,[39] the principal investigator sampled the air near the top of the aerator for volatile solvents and identified trichloroethylene, tetrachloroethylene, 1,1,1-trichloroethane, and 1,2-dichloroethane. The mean concentrations of the solvents were far below allowable occupational exposures.[42] This air sampling program is continuing, but the likelihood of creating an air pollution problem by aerating solvent-contaminated drinking water is remote given existing air quailty standards. Another topic of investigation by USEPA-DWRD is the potential for water quality deterioration from airborne particulates, oxidized inorganics, and microbiological growth in the aeration device. Although these are not thought to be significant problems, they are being investigated to understand more fully the aeration process.

Adsorption. Like aeration, adsorption has a spectrum of effectiveness (Figure 11). However, adsorption is more complicated than aeration, and water quality can have a definite influence on its performance. Figure 12 summarizes the data from several adsorption isotherm studies,[43-45] and for purposes of illustration, the adsorption capacity for each contaminant is shown at an equilibrium concentration of 500 μg/L. Table 6 incorporates

TABLE 8

Estimated air-to-water ratios necessary to achieve desired treatment—summary

Compound	Influent Concentration μg/L	Effluent Concentration—μg/L: 0.1 a*	0.1 b†	0.1 c‡	1 a	1 b	1 c	10 a	10 b	10 c	50 a	50 b	50 c	100 a	100 b	100 c
Trichloroethylene	1000	2:1	40–136:1	76:1	2:1	25–100:1	54:1	2:1	10–66:1	32:1	2:1	4–44:1	17:1	2:1	3–34:1	11:1
	100	2:1	25–100:1	54:1	2:1	10–66:1	32:1	2:1	3–34:1	11:1	<1:1	1–10:1	1:1	<1:1		
	10	2:1	10–66:1	32:1	2:1	3–34:1	11:1									
	1	2:1	3–34:1	11:1												
Tetrachloroethylene	1000	1:1	25–320:1	96:1	1:1	17–150:1	72:1	<1:1	11–65:1	45:1	<1:1	8–36:1	26:1	<1:1	6–30:1	18:1
	100	1:1	17–150:1	72:1	1:1	11–65:1	45:1	<1:1	6–30:1	18:1	<1:1	2–7:1	1:1			
	10	1:1	11–65:1	45:1	1:1	6–30:1	18:1									
	1	1:1	6–30:1	18:1												
1,1,1-Trichloroethane	1000	6:1	60–600:1	198:1	6:1	21–260:1	90:1	6:1	10–120:1	35:1	6:1	5–65:1	14:1	6:1	4–52:1	8:1
	100	6:1	21–260:1	90:1	6:1	10–120:1	35:1	6:1	4–52:1	8:1	4:1	1–15:1	1:1			
	10	6:1	10–120:1	35:1	6:1	4–52:1	8:1									
	1	6:1	4–52:1	8:1												
Carbon tetrachloride	1000	1:1		19:1	1:1		15:1	1:1		10:1	1:1		6:1	<1:1		4:1
	100	1:1		15:1	1:1		10:1	1:1		6:1	<1:1		1:1			
	10	1:1		10:1	1:1		6:1									
	1	1:1		6:1												
cis-1,2-Dichloroethylene	1000	4:1	14–152:1	104:1	9:1	10–115:1	77:1	4:1	8–76:1	52:1	4:1	5–50:1	34:1	4:1	4–38:1	26:1
	100	4:1	10–115:1	77:1	4:1	8–76:1	52:1	4:1	4–38:1	26:1	2:1	2–10:1	4:1			
	10	4:1	8–76:1	52:1	3:1	4–38:1	26:1									
	1	3:1	4–38:1	26:1												
1,2-Dichloroethane	1000	20:1		56:1	20:1		42:1	20:1		28:1	20:1		18:1			14:1
	100	20:1		42:1	20:1		28:1	18:1		14:1	10:1					
	10	20:1		28:1	18:1		14:1									
	1	18:1		14:1												

*Theoretical optimum air-to-water ratio based on the reciprocal of the Henry's law constants given by Dilling.[38] An explanation of this concept is found elsewhere.[45]
†Range of air-to-water ratios extrapolated from actual experimentation. This is estimated by developing an envelope around the data in Figures 8, 9, and 10.
‡Average air-to-water ratio calculated from *b*

TABLE 9

Estimated carbon usage necessary to achieve desired treatment—summary

Compound	Influent Concentration μg/L	Desired Effluent Concentration—μg/L: 0.1 a*	0.1 b†	1 a	1 b	10 a	10 b	50 a	50 b	100 a	100 b
Trichloroethylene	1000	5.7–10.5	6.9 (0.50)	7.8–11.3	8.7 (0.4)	9.8–12.2	10.4 (0.32)	11.2–12.7	11.6 (0.29)	11.8–13.0	12.1 (0.28)
	100	13.8–25.3	16.7 (0.20)	20.2–27.9	22.1 (0.15)	26.7–30.5	27.7 (0.12)	31.2–32.3	31.5 (0.11)		
	10	33.1–64.6	41.0 (0.08)	56.3–72.1	60.3 (0.06)						
	1	79.4–146	96.1 (0.03)								
1,1,1-Trichloroethane	1000	0.17–6.1	1.7 (2.0)	0.19–7.5	2.6 (1.3)	0.2–8.9	3.3 (1.0)	0.21–9.9	3.9 (0.86)	0.22–10.3	4.2 (0.80)
	100	0.79–28.0	8.1 (0.41)	0.88–36.0	13.0 (0.26)	0.98–45.0	18.0 (0.19)	1.1–51.0	21.0 (0.16)		
	10	3.6–127	37.0 (0.09)	4.3–186	70.0 (0.05)						
	1	16.0–580	169 (0.02)								
Tetrachloroethylene	1000	10.6–16.2	14.7 (0.23)	17.7–21.8	20.7 (0.16)	24.7–27.5	26.7 (0.13)	29.5–31.4	30.9 (0.11)	31.7–33.2	32.7 (0.10)
	100	29.2–44.4	40.1 (0.08)	55.0–66.7	59.6 (0.06)	80.6–83.8	81.2 (0.41)	99.0–101	100 (0.03)		
	10	80.4–122	111 (0.03)	186–208	200 (0.02)						
	1	221–337	306 (0.01)								
Carbon tetrachloride	1000	2.9–6.6	4.8 (0.7)	5.0–7.9	6.5 (0.51)	7.2–9.2	8.2 (0.41)	8.8–10.1	9.5 (0.35)	9.3–10.5	9.9 (0.34)
	100	4.3–9.8	7.0 (0.48)	8.8–12.3	10.6 (0.32)	13.2–14.8	14.0 (0.24)	16.1–16.6	16.3 (0.21)		
	10	6.4–14.4	10.4 (0.32)	16–20.1	18.0 (0.19)						
	1	9.5–21.4	15.5 (0.22)								
cis-1,2-Dichloroethylene	1000	0.6–1.4	1.1 (3.0)	1.0–1.6	1.3 (2.6)	1.4–1.9	1.5 (2.2)	1.4–2.0	1.7 (2.0)	1.5–2.1	1.8 (1.9)
	100	1.8–4.4	3.3 (1.0)	3.5–5.3	4.2 (0.8)	4.4–6.2	5.2 (0.65)	4.7–6.9	5.9 (0.55)		
	10	5.5–13.5	10.1 (0.3)	13.0–17.8	14.6 (0.2)						
	1	17.0–41.6	31.1 (0.1)								
1,2-Dichloroethane	1000	0.8–5.2	2.0 (1.7)	1.3–7.0	3.1 (1.1)	1.7–9.0	4.1 (0.82)	2.0–11.1	4.9 (0.68)	2.2–12.0	5.2 (0.65)
	100	1.1–8.4	3.5 (1.0)	2.2–13.0	5.4 (0.62)	3.0–17.6	7.3 (0.46)	3.6–20.8	8.6 (0.39)		
	10	1.6–12.5	5.2 (0.65)	3.8–22.6	9.3 (0.36)						
	1	2.4–18.4	7.6 (0.45)								

*The range of granular activated carbon usage given in units of 10^3 m^3 water/m^3 carbon; estimated from isotherm data given by Dobbs and Cohen[40] and empirical data in Table 6
†Mean GAC usage given in units of 10^3 m^3 water/m^3 carbon (lb carbon/10^3 gal water)

these isotherm data with available empirical data (mostly from pilot-scale studies),[46,47] so actual loadings can be compared with theoretical loadings. Even though the isotherm capacities represent pure compound adsorption without competition, and the empirical capacities represent adsorption in competition with background organics, in most cases, the actual loadings are higher than those predicted from the isotherm. This was unexpected, and the difference is perhaps the result of biodegradation. Nonetheless, competitive adsorption is not well understood and future adsorption studies by USEPA-DWRD will investigate more thoroughly the effects of competition between trichloroethylene-related volatile organics and the nonvolatile background organic carbon.

The removal of organic contaminants by means of the Ambersorb resin looks promising. Studies have shown that the capacity of this resin for most of these contaminants (Table 7) is typically two to three times that of GAC (on a weight basis) for control to breakthrough. Whether it can be regenerated economically by steam is the topic of ongoing research[39,48] and may not be known for some time. Effectiveness of the synthetic resin, like that of GAC, is influenced by the quality of the applied water. Resin capacity may be reduced at the high pH of lime softening[30] and when competition exists for the adsorption sites.[11] The

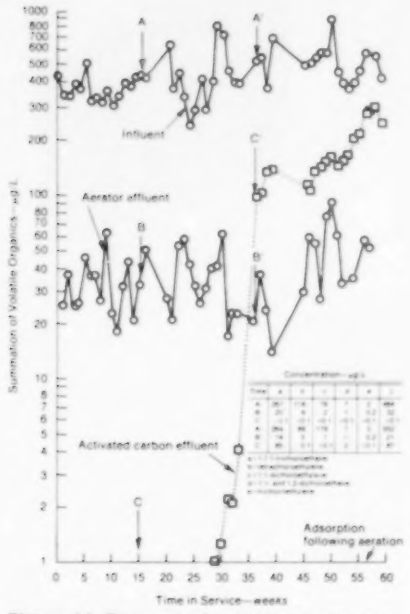


Figure 11. Removal of volatile organic compounds by aeration and adsorption on granular activated carbon

Pilot-scale study with New Jersey groundwater; aeration: 4:1 (vol:vol); adsorption on GAC; EBCT = 18 min

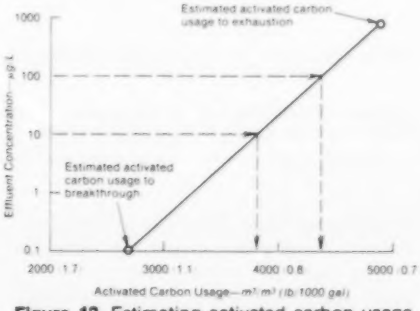
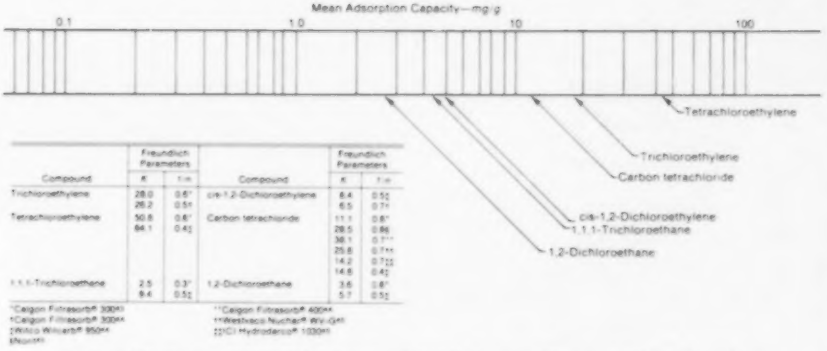

Estimated activated carbon usage to exhaustion
Estimated activated carbon usage to breakthrough
Effluent Concentration—μg/L
Activated Carbon Usage—m³/m³ (lb/1000 gal)

Figure 13. Estimating activated carbon usage to achieve target effluent qualities

1,1,1-Trichloroethane initial concentration = 1000 μg/L



Compound	Freundlich Parameters K	1/n	Compound	Freundlich Parameters K	1/n
Trichloroethylene	28.0	0.6*	cis-1,2-Dichloroethylene	6.4	0.5‡
	26.2	0.5†		6.5	0.7†
Tetrachloroethylene	50.8	0.6*	Carbon tetrachloride	11.1	0.8*
	64.1	0.4‡		28.5	0.8§
				36.1	0.7††
				25.8	0.7††
				14.2	0.7‡‡
				14.6	0.4‡
1,1,1-Trichloroethane	2.5	0.3*	1,2-Dichloroethane	3.6	0.8*
	8.4	0.5‡		5.7	0.5‡

*Calgon Filtrasorb® 300(H)
†Calgon Filtrasorb® 300(H)
‡Witco Witcarb® 950(H)
§Norit(H)
††Calgon Filtrasorb® 400(H)
†††Westvaco Nuchar® WV-G(H)
‡‡‡ICI Hydrodarco® 1030(H)

Figure 12. Comparison of isotherm adsorption capacities on activated carbon

Equilibrium concentration = 500μg/L

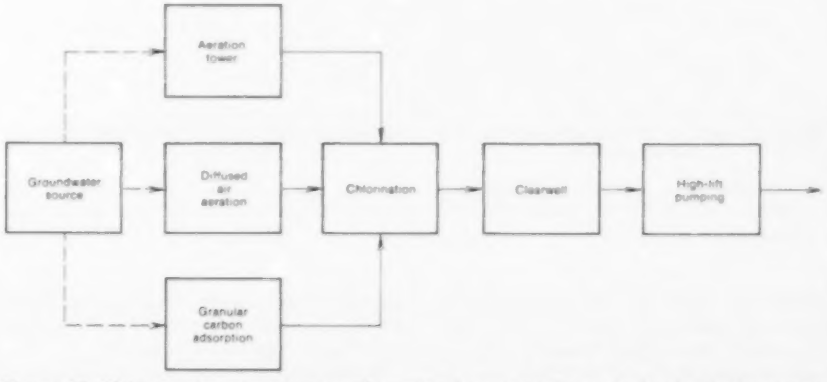


Figure 14. Water treatment system configuration for economic analysis of volatile organic contaminant removal

effects of applying chlorinated water to the synthetic resin are not known but should be investigated before the product is approved for use on potable water.

Concern has been expressed regarding contaminants that concentrate on an adsorbent and then detach because of changing conditions. Abrupt desorption did not occur during the studies reported in this paper. However, researchers[11,31,39,46] have observed periods when the effluent concentration of an organic can exceed its influent value after passing through an adsorbent. This phenomenon is not apparent from Figure 11, in which the organic concentrations were added together to assess overall performance, but some desorption is evident when the behavior of an individual solvent is examined (Figure 7 after week 50 on the unaerated flow stream and Figure 4 between weeks 40 and 50). In these examples, the concentration of 1,1,1-trichloroethane in the effluent from the GAC adsorber is higher than that in the influent. In agreement with what others[11,31,39,46] have observed, an increased effluent concentration occurs when the influent concentration of adsorbate declines, and the resulting desorption or "leakage" can be explained by adsorption equilibrium theory.

Estimated treatment costs

In any economic analysis, the cost data presented are dependent on particular

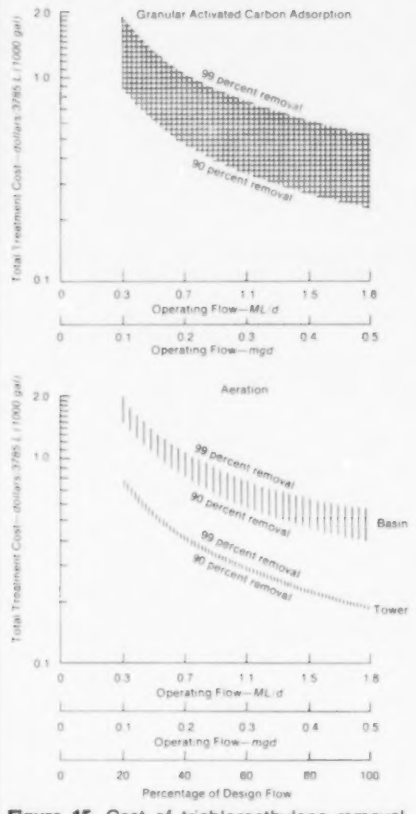


Figure 15. Cost of trichloroethylene removal (90–99 percent)

October 1980 dollars; influent concentration of 1–1000 μg/L; design flow of 1.8 ML/d (0.5 mgd)

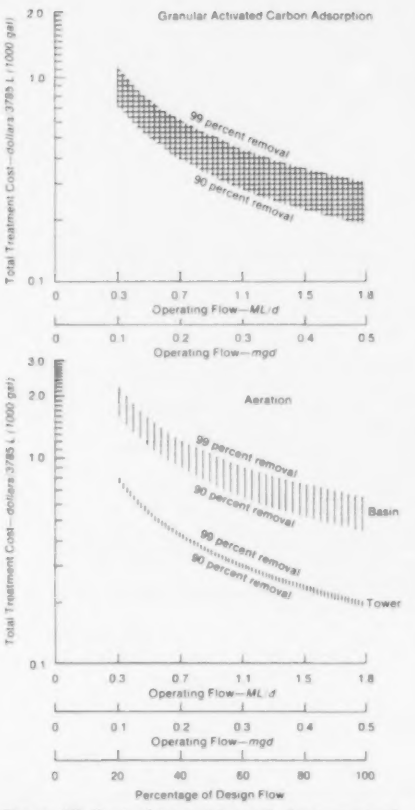


Figure 16. Cost of tetrachloroethylene removal (90–99 percent)

October 1980 dollars; influent concentration of 1–1000 μg/L; design flow of 1.8 ML/d (0.5 mgd)

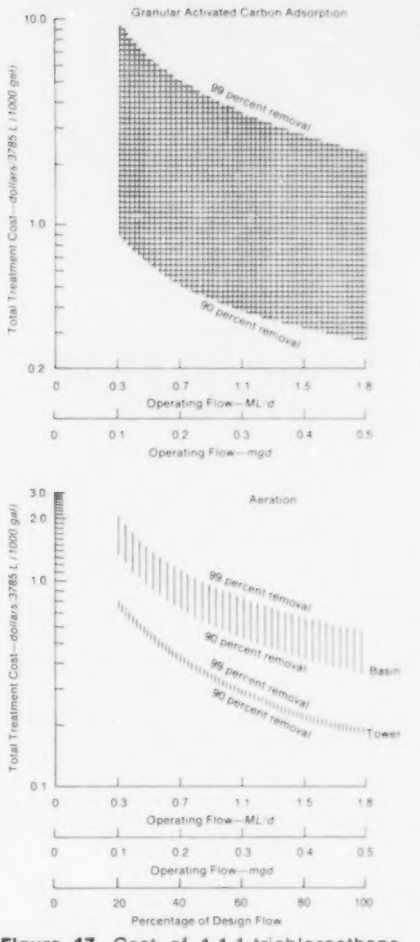


Figure 17. Cost of 1,1,1-trichloroethane removal (90–99 percent)

October 1980 dollars; influent concentration of 1–1000 μg/L; design flow of 1.8 ML/d (0.5 mgd)

design assumptions. For example, the costs associated with aeration are sensitive to the removal efficiencies and can vary significantly depending on the design parameters selected by the cost analyst and onsite-specific considerations. Therefore, the cost estimates presented in this paper should be viewed as a preliminary attempt to quantify the economics of removing trichloroethylene and related solvents from drinking water.

The first step in estimating cost was to develop a treatment matrix. Influent concentrations were selected, and the treatment necessary to achieve hypothetical effluent qualities* was then determined. For aeration, air-to-water ratios were estimated (Table 8) by developing an envelope around the empirical data in Figures 8, 9, and 10 and extrapolating for the higher removal efficiencies.

Estimating the GAC usage necessary to achieve hypothetical target levels (Table 9) was more complicated. First, two ratios were established for each contaminant: ratio *a* was the capacity at exhaustion observed from field studies divided by theoretical capacity determined from isotherm data,[43] and ratio *b* was the capacity at actual exhaustion divided by capacity at actual breakthrough (Table 6). Second, isotherm capacities at the given contaminant concentrations (1000, 100, 10, and 1 μg/L) were multiplied by ratio *a* to give an estimated GAC usage to exhaustion, then that value was divided by ratio *b* to give an estimated GAC usage to breakthrough. Third, GAC usage for intermediate effluent concentrations was estimated from a semilog plot (Figure 13).

The ranges of estimated aeration requirements and GAC usage shown in Tables 8 and 9 are extremely wide for certain contaminant concentrations, so on-site pilot-scale experimentation would be prudent if treatment by either process is contemplated. However, the data allow some preliminary estimates of treatment costs by using computer cost programs developed by Gumerman et al.[39]

The cost analysis is based on a flow of 1.8 ML/d (500 000 gpd), with the treatment system shown in Figure 14. The groundwater is treated by tower aeration, diffused-air aeration, or adsorption on GAC followed by chlorination, clearwell storage, and high-lift pumping. The aeration towers are rectangular with an overall height of 3 m (10 ft), and an air supply of 137 L/min/m^2 (52 scfm/sq ft) of surface area is assumed. They have electrically driven induced-draft fans, fan stacks, and drift eliminators. Costs of supply pumps or underflow pumps are

*Maximum contaminant levels have not been established for the trichloroethylene-related organic compounds. However, the USEPA Office of Drinking Water has developed "Health Advisories" and has proposed[1] possible ranges for lifetime exposure to selected organic chemicals.

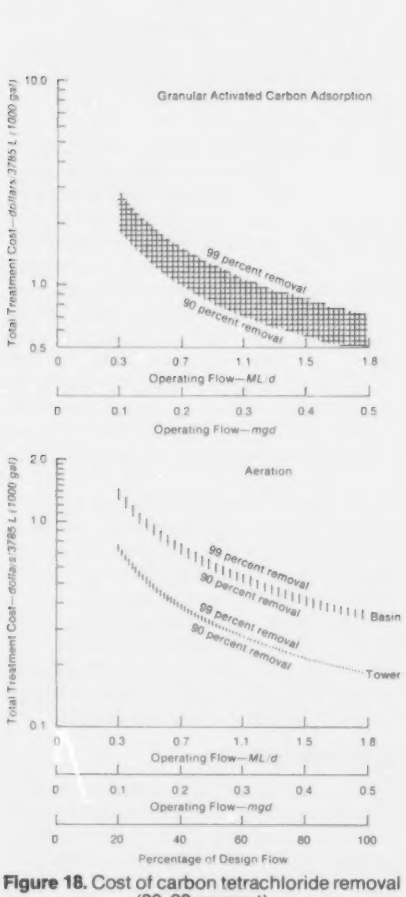


Figure 18. Cost of carbon tetrachloride removal (90–99 percent)

October 1980 dollars; influent concentration of 1–1000 μg/L; design flow of 1.8 ML/d (0.5 mgd)

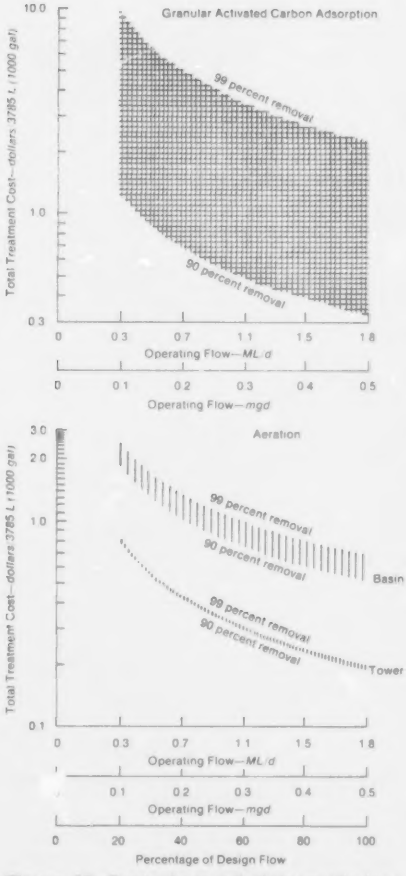


Figure 19. Cost of cis-1,2-dichloroethylene removal (90–99 percent)

October 1980 dollars; influent concentration of 1–1000 μg/L; design flow of 1.8 ML/d (0.5 mgd)

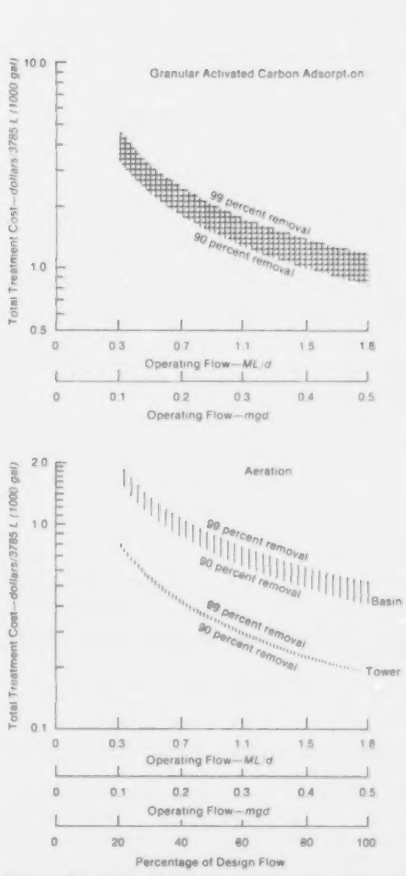


Figure 20. Cost of 1,2-dichloroethane removal (90–99 percent)

October 1980 dollars; influent concentration of 1–1000 μg/L; design flow of 1.8 ML/d (0.5 mgd)

not included. The aeration basins are rectangular with a depth of 3.5 m (12 ft). The diffused air supply system was sized for 14 L/min/m^2 (5 scfm/sq ft) of basin flow area. Adsorption consists of three steel contactors in series with an initial supply of GAC. GAC usage is based on six-month throwaway at a cost of $1.50/kg ($0.70/lb). Chlorination consists of a feed system (no basin) and a building for cylinder storage. A chlorine dose of 2 mg/L is assumed and the cost of chlorine is $0.35/kg ($320/ton). Clearwell storage is above ground, with a capacity equal to 10 percent of the daily plant flow. The high-lift pumping has a head of 12 m (40 ft). The estimated treatment cost does not include expenditures for land, slime or corrosion control, fences, exhaust gas handling, or carbon disposal.

Figures 15 through 20 depict the total treatment cost in dollars per 3785 L (1000 gal) of treated water as a function of operating flow. Each figure shows the costs in October 1980 dollars for 90–99 percent removal by aeration towers, aeration basins, and adsorption with an influent contaminant concentration varying from 1 to 1000 μg/L. For costing purposes the required volumes for aeration basins and towers were computed as a function of the mean air-to-water ratios in Table 8. The ranges of costs for aeration towers are narrow because little economy-of-scale exists for operating these units at such small hydraulic loadings.

The GAC requirements were the mean values given in Table 9. The costs for adsorption cover wider ranges than those estimated for aeration because of the influence of contaminant concentration. For example, the cost of 90 percent removal by aeration is the same whether the contaminant concentration is reduced from 1000 to 100 μg/L or from 1 to 0.1 μg/L. Adsorption capacity and GAC usage, however, vary with contaminant concentrations. Therefore, the cost of 90 percent removal by GAC is higher if the influent concentration is 1000 μg/L compared with 100 μg/L. Moreover, the cost for adsorption covers a wide range because of the poor adsorbability associated with some contaminants. High percentages of removal for the poorly adsorbed contaminants require large amounts of GAC, and this increases the cost of treatment.

Figure 21 illustrates another way of presenting the information given in Figures 15–20. The total treatment cost of trichloroethylene removal is shown as a function of influent concentration at four levels of effluent concentration for each of the three treatment modes. Similar graphs could be generated for the other contaminants. Figure 22 shows the total treatment cost of trichloroethylene removal versus treatment plant size for

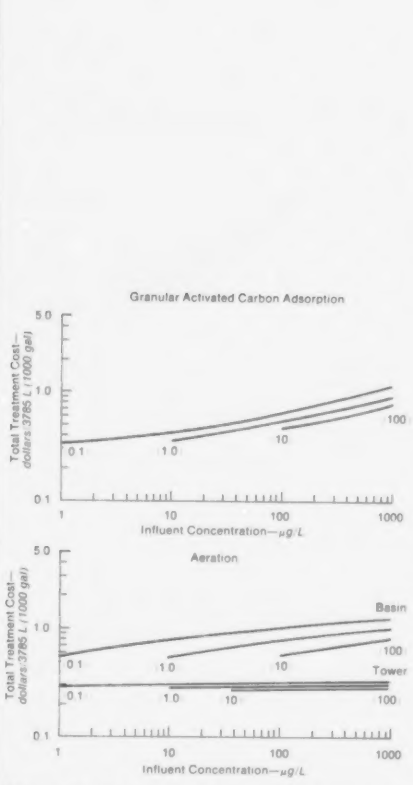


Figure 21. Cost of trichloroethylene removal

October 1980 dollars; effluent concentrations of 0.1–100 μg/L; design flow of 1.8 ML/d (0.5 mgd) operating at 60 percent capacity; numbers in parentheses are effluent concentrations in μg/L

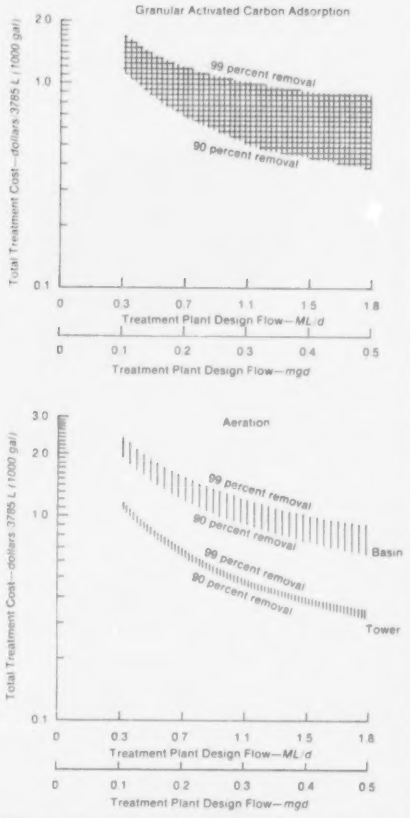


Figure 22. Cost of trichloroethylene removal (90–99 percent)

October 1980 dollars; influent concentration of 1–1000 μg/L; operating flow is 50 percent of design flow

TABLE 10
Relative effectiveness of treatment*

Compound	Aeration		Adsorption			Boiling
			Granulated Activated Carbon		Synthetic Resin	
	Predicted from Henry's Law Constant	Pilot-Scale Experience	Predicted from Isotherm Data	Pilot-Scale Experience	Pilot-Scale Experience	
Trichloroethylene	3	2	2	1	1	5
Tetrachloroethylene	2	1	1	2	2	1
1,1,1-Trichloroethane	5	5	6	5	5	4
Carbon tetrachloride	1	3	3	3	6	3
cis-1,2-Dichloroethylene	4	4	5	6	4	2
1,2-Dichloroethane	6	6	4	4	3	

*1 = best performance; 6 = poorest performance

each type of treatment. Operating flow is 50 percent of design flow for these data, with an influent concentration of 1 to 1000 μg/L. Similar information can be generated for the other contaminants.

Summary

Trichloroethylene and related solvents occur in both untreated and treated drinking water. In general, groundwaters rather than surface waters are more likely to have significant concentrations of these compounds, with some possible exceptions: when a river is frozen over and volatile organics cannot escape into the atmosphere, when upstream spills occur, or when products used to treat or transport the water have contaminants.

The seriousness of having these organics in drinking water, and thus the establishment of acceptable limits, is a current topic of concern to USEPA[1] and may not be resolved for some time. In the interim, however, research continues to investigate the effectiveness of different water treatment processes in removing volatile organics. Such information might be helpful, for example, to a utility faced with the option of seeking an alternative source of water or providing treatment.

Table 10 lists the treatment processes and their relative effectiveness for removing or reducing the concentrations of six volatile organics found in drinking water. Although conventional treatment (coagulation, sedimentation, and filtration) has been found to be ineffective for control of these organics, they can be removed by aeration, adsorption on GAC or the Ambersorb resin, or combinations of these processes. Results from studies of adsorption preceded by aeration seem encouraging (Figure 11), and this combination may be the one needed for treating certain waters. At the point of use, boiling can remove these solvents, but at least five minutes of vigorous boiling in a well-ventilated area is required.

Preliminary estimates of costs vary significantly, depending on treatment process and contaminants and amplify the need for thorough organic analysis and site-specific performance data.

Acknowledgments

The cooperation and assistance provided by water utility and regulatory personnel in the states of Connecticut, New Hampshire, Rhode Island, and New Jersey are greatly appreciated.

Special recognition is expressed to C.D. Larson, USEPA, Region I, Boston, Mass., and M. Haupman, Region II, New York, N.Y., for their help in conducting the field studies. K.L. Kropp and B.L. Smith, DWRD staff members, contributed considerable time and effort to this work.

The efforts of M.M. Lilly for typing this manuscript and J.M. Symons, A.A. Stevens, G.G. Robeck, W.A. Feige, R.M. Clark, R.J. Miltner, J. Westrick, and T. Thornton for providing valuable editorial and technical comments are acknowledged.

References*

1. National Revised Primary Drinking Water Regulations, Volatile Synthetic Organic Chemicals in Drinking Water. *Federal Register*, 47:43:9350 (Mar. 4, 1982).
2. SEEGER, D.R.; SLOCUM, C.J.; & STEVENS, A.A. GC/MS Analysis of Purgeable Contaminants in Source and Finished Drinking Water. Proc. 26th Ann. Conf. on Mass

*Unpublished reports and sponsored project information are available from: Director, Drinking Water Research Division, Municipal Environmental Research Laboratory, Office of Research and Development, USEPA, 126 West St. Clair St., Cincinnati, OH 45268.

Spectrometry and Applied Topics, St. Louis, Mo. (May 1978).
3. DUNLAP, W. Preliminary Laboratory Study of Transport and Fate of Selected Organics in a Soil Profile. Groundwater Res. Ctr., USEPA, Ada, Okla. (1980).
4. ROBERTS, P.V.; SCHREINER, J.; & HOPKINS, G.D. Field Study of Organic Water Quality Changes During Groundwater Recharge in the Palo Alto Baylands. Symposium on Waste Water Reuse for Groundwater Recharge, Pomona, Calif. (Sept. 1979).
5. CHIOU, C.T.; PETERS, L.J.; & FREED, V.H. A Physical Concept of Soil-Water Equilibria for Nonionic Organic Compounds. *Science*, 206:831 (Nov. 1979).
6. SYMONS, J.M. ET AL. National Organics Reconnaissance Survey for Halogenated Organics in Drinking Water. *Jour. AWWA*, 67:11(Part I):634 (Nov. 1975).
7. JAREMA, R. Plainville and Plainfield's Plight with Pollution. Connecticut State Dept. of Health, Hartford (July 1977).
8. JOHNSON, D. ET AL. Chemical Contamination. Special Legislative Comm. on Water Supply, The Commonwealth of Massachusetts, Boston (Sept. 1979).
9. KIM, N.K. & STONE, D.W. Organic Chemicals in Drinking Water. New York State Dept. of Health, Albany (1980).
10. LANG, R.F. ET AL. Introductory Study of the Biodegradation of the Chlorinated Methane, Ethane and Ethene Compounds. Proc. AWWA Ann. Conf., St. Louis, Mo. (June 1981).
11. SYMONS, J.M. ET AL. Removal of Organic Contaminants from Drinking Water Using Techniques Other Than Granular Activated Carbon Alone—A Progress Report. *Proceedings, Practical Application of Adsorption Techniques in Drinking Water*. USEPA, Ofce. Drinking Water, Washington, D.C. (in press).
12. CRANE, A.M. & FREEMAN, A.F. Water Softening and Conditioning Equipment: A Potential Source of Water Contamination. EPA Rept. EPA-600/3-77-107. USEPA, Gulf Breeze, Fla. (Mar. 1977).
13. Control of Organic Chemical Contaminants in Drinking Water. *Federal Register*, 43:28:5759 (Feb. 9, 1978).
14. CAIRO, P.R. ET AL. Is Your Chlorine Safe to Drink? *Jour. AWWA*, 71:8:450 (Aug. 1979).
15. LARSON, C.D.; LOVE, O.T. JR; & REYNOLDS, G.B. Tetrachloroethylene From Lined Asbestos Cement Pipe. Proc. USEPA Technology Transfer Sem. Corrosion Control in Water Distribution Systems. USEPA, Cincinnati, Ohio (May 1980).
16. SYLVIA, A.E. Personal communication (1980).
17. *Azeotropic Data-II*. Advances in Chemistry Series, No. 35 (R.F. Gould, editor). ACS, Washington, D.C. (1962).
18. Innovative and Alternative Technology Assessment Manual (Draft). EPA Rept. EPA-430/9-78-009. USEPA, Cincinnati, Ohio (1978).
19. WARNER, P.H.; COHEN, J.M.; & IRELAND, J.C. Determination of Henry's Law Constants of Selected Priority Pollutants. Ofce. Res. Devel., Municipal Environ. Res. Lab., USEPA, Cincinnati, Ohio (Apr. 1980).
20. DILLING, W.L. Interphase Transfer Processes. II. Evaporation Rates of Chloro Methanes, Ethanes, Ethylenes, Propanes, and Propylenes from Dilute Aqueous Solutions. Comparisons With Theoretical Predictions. *Environ. Sci. & Technol.*, 11:4:405 (Apr. 1977).
21. ZOETEMAN, B.C.J. Threshold Odour Concentrations in Water of Chemical Substances. R.I.D.-Medeleling 74-3. Natl. Inst. Water, Leidschendam, The Netherlands (1974).
22. STAHL, W.H. Compilation of Odor and Taste Threshold Values Data. Data Series DS48 (05-048000-36). ASTM, Philadelphia, Pa. (May 1973).
23. KELLER, P.A. Threshold Odor Concentration for Carbon Tetrachloride in Drinking Water. Ofce. Res. Devel., Municipal Environ. Res. Lab., Drinking Water Res. Div., USEPA, Cincinnati, Ohio (1977). (Unpublished).
24. KITTSLEY, S.L. *Physical Chemistry*. Barnes and Noble, Inc., New York (2nd ed., 1967).
25. *The Merck Index*. Merck & Co., Inc., Rahway, N.J. (9th ed., 1976).
26. *NIOSH Register of Toxic Effects of Chemical Substances*. Vol. 2. US Dept. of Health, Education and Welfare, Public Health Service, CDC, Natl. Inst. of Occupational Safety and Health. Cincinnati, Ohio (Sept. 1977).
27. MERRICK, E.T. ET AL. EPA Chemical Activities Status Report. Toxic Integration Information Series. EPA 560/13-79-003. USEPA, Washington, D.C. (1st ed., Apr. 1979).
28. *Kirk-Othmer Encyclopedia of Chemical Technology*. Vol. 5. John Wiley & Sons, New York (3rd ed., 1979).
29. Preliminary Study of Selected Potential Environmental Contaminants—Optical Brighteners, Methyl Chloroform, Trichloroethylene, Tetrachloroethylene, Ion Exchange Resins. EPA Rept. EPA 560/2-75-002 (PB 243-910). Ofce. of Toxic Substances, USEPA, Washington, D.C. (July 1975).
30. FLEISHER, M.B. & MACKAY, S.L. Assessment of the Impact of Organic Solvent Cesspool Cleaners and Drain Operators on Nassau County Drinking Water Supplies. Nassau County Dept. of Health, Mineola, N.Y. (Dec. 1977).
31. WOOD, P.R. & DEMARCO, J. Effectiveness of Various Adsorbents in Removing Organic Compounds from Water—Part I—Removing Purgeable Halogenated Organics. *Activated Carbon Adsorption of Organics from the Aqueous Phase*. Vol. 2. Ann Arbor Science Publishers, Inc., Ann Arbor, Mich. (1980).
32. The Analysis of Trihalomethanes in Drinking Waters by Purge and Trap Method. Method 501.1. EMSL, USEPA, Cincinnati, Ohio (1979).
33. SINGLEY, J.E.; BEAUDET, B.A.; & ERVIN, A.L. Use of Powdered Activated Carbon for Removal of Specific Organic Compounds. Proc. AWWA Ann. Conf., San Francisco (June 1979).
34. LYKINS, B.W. & DEMARCO, J. An Overview of the Use of Powdered Activated Carbon for Removal of Trace Organics in Drinking Water. Ofce. Res. Devel., Municipal Environ. Res. Lab., Drinking Water Res. Div., USEPA, Cincinnati, Ohio (unpublished draft, 1980).
35. LATAILLE, M. The Effect of Boiling on Water Contaminated with Chlorinated Solvents. Mimeographed. USEPA, Region I, Lexington, Mass. (Dec. 4, 1979).
36. COMBS, W.S. Removal of Chlorinated Solvents from Water by Boiling. Mimeographed. State of Rhode Island and Providence Plantations, Dept. of Health, Providence (Feb. 5, 1980.)
37. LYKINS, B.W. Summary of Short-Term Experimental Modes of Operation—Evansville, Indiana. Draft Interim Rept. for EPA Grant R804902. Ofce. Res. Devel., Municipal Res. Lab., Drinking Water Res. Div., USEPA, Cincinnati, Ohio (May 1979). (Unpublished).
38. MCCARTY, P.L. ET AL. Volatile Organic Contaminants Removal by Air Stripping. Proc. AWWA Ann. Conf., San Francisco (June 1979).
39. RUGGIERO, D.D. & FEIGE, W.A. Use of Aeration and Resin Treatment of a Ground Water. Proc. AWWA Ann. Conf., Atlanta, Ga. (June 1980).
40. KELLEHER, D.L.; STOVER, E.L.; & SULLIVAN, M. Investigation of Volatile Organics Removal. *Jour. New England Water Works Assn.*, 95:2:119 (June 1981).
41. SYMONS, J.M. ET AL. Treatment Techniques for Controlling Trihalomethanes in Drinking Water. EPA Rept. EPA-600/2-81-156. USEPA, Cincinnati, Ohio (Sept. 1981).
42. US Dept. of Labor, Occupational Safety and Health Admin. General Industry Standards. *Federal Register*, 29:1910 (1978).
43. DOBBS, R.A. & COHEN, J.M. Carbon Adsorption Isotherms for Toxic Organics. EPA Rept. EPA-600/8-80-023. USEPA, Cincinnati, Ohio (Apr. 1980).
44. MILTNER, R.J. Personal communication (1981).
45. WEBER, W.W. & PIRBAZARI, M. Effectiveness of Activated Carbon for Removal of Toxic and/or Carcinogenic Compounds from Water Supplies. EPA Rept. EPA-600/2-81-057. USEPA, Cincinnati, Ohio (Jan. 1981).
46. SYMONS, J.M. Interim Treatment Guide for Controlling Organic Contaminants in Drinking Water Using Granular Activated Carbon. Ofce. Res. Devel., Municipal Environ. Res. Lab., Drinking Water Res. Div., USEPA, Cincinnati, Ohio (Jan. 1978).
47. DEMARCO, J. & BRODTMANN, N.V. Prediction of Full-Scale Plant Performance from Pilot Columns. *Proceedings, Practical Application of Adsorption Techniques in Drinking Water*. USEPA, Ofce. Drinking Water, Washington, D.C. (in press).
48. NEELY, J.W. & ISACOFF, E.G. Regenerability of Ambersorb XE-340. New Jersey AWWA Section Meeting, Atlantic City (Sept. 1979).
49. GUMERMAN, R.C.; CULP, R.L.; & HANSEN, S.P. Estimating Water Treatment Costs. Research Reporting Series. EPA-600/2-79-162. USEPA, Cincinnati, Ohio (Aug. 1979).

O. Thomas Love Jr. is chief of organic control—exploratory activities and Richard G. Eilers is an operations research analyst with economic analysis activities, Physical and Chemical Contaminant Removal Branch, Drinking Water Research Division, Municipal Environmental Research Laboratory, Office of Research and Development, US Environmental Protection Agency, Cincinnati, OH 45268.

This article documents research that was conducted under the auspices of the U.S. Environmental Protection Agency (USEPA). As an arm of the government, the USEPA has a paid up, non-exclusive, irrevocable, worldwide license to reproduce, prepare derivative works, and distribute to the public all of the material contained herein, and to grant others acting on its behalf the right to do so. The USEPA grants to the National Technical Information Service, Department of Commerce, the right to act as its agent in the distribution of this material.